

Saga of the Cassini Engine Gimbal Actuator

How to Succeed Even When you Plan to

Abstract

The evolution of a linear servomotor design is presented. Beginning with requirements that pushed the envelope of known mechanism flight duration, the Cassini project sought out a reliable linear actuator for positioning its redundant rocket engines. Options from commercial off-the-shelf (COTS) hardware to in-house designs were pursued. A device inherited from JPL's Mariner and Viking Mars missions was selected for its close match to functional requirements and its flight pedigree. Several design improvements were necessary to ensure life and reliability goals would be met. These improvements and, in particular, efforts to develop new component sources are discussed. Special attention was focused on reliability testing of the motor and mechanism at all stages of procurement and assembly because a brush type DC motor was retained in the new design.

Background

The Cassini-Huygens mission to Saturn is a joint effort between NASA and the European Space Agency. The spacecraft is a de-scoped version of CRAF/Cassini, which would have also flown a separate comet rendezvous mission.

Cassini uses a redundant pair of rocket engine thrusters supplied by the Kaiser-Marquardt company. The two 400 N thrusters are mounted in a Rocket Engine Assembly (REA). The REA provides thrust Vector Control for the spacecraft.

- In-course trajectory adjustments
- The Saturn Orbit Insertion maneuver
- Saturn orbit trajectory control

The REA comprises redundant two-axis gimbal subsystems. Each gimbal subsystem includes fuel lines, filters, bearings, structure, and two Engine Gimbal Actuators (EGAs). The EGAs are furnished by JPL to Lockheed-Martin in Denver, Co. who designed and built the REA (Figure) and the larger Propulsion Module Subsystem into which the REA fits.

JPL had to choose between either procuring a complete EGA or building the assembly with purchased components. The Engine Gimbal Electronics for control of the EGAs, was designed and built at JPL because we had access to large selections of screened and rad-hard electronic parts.

Two salient considerations drove our decision process: "short schedule and uncertainty of requirements." Our schedule was critical because, as noted above, we had to deliver tested and proven actuators to JPL's subcontractor in time for it to perform the necessary subsystem (level) tests.

We prepared a Request for Proposal (RFP) while requirements were still fluid. This process took much longer than anticipated because we were not converging on a firm set of requirements that should constitute a good specification. Fundamental issues such as launch vibration forces, mass, and power were irreconcilable.

The RFP was never sent out, but several vendors were solicited for specifications of their existing linear actuators. As we pushed hard to define a workable set of requirements, it became apparent that our application fit into a design space that did not suit any commercial designs. Instead, some modifications to an existing JPL design, the Mariner Mars/Viking Orbiter (MMVO) actuator, which successfully flew on three spacecraft destined for Mars, promised to satisfy all the design constraints. The following narrative is interspersed with lessons learned as we proceeded with our decisions and design process.

Setting the Course/

Mariner actuator and US patent

When first published in 1971, the MMVO linear actuator design was novel enough to earn United States Patent No. 3,660,704 (Figure 1). The patent was granted on the basis of improved reliability, responsiveness, and lower weight compared to existing technology. These characteristics were partly achieved by using a DC brush motor whose rotor is mounted directly on the nut of a ball screw, instead of driving through a conventional geartrain. Features which accrued to this design because of the direct drive approach include a single duplex pair bearing and dust seals between mechanism and motor brush dust. In addition to the drive mechanism, the device's output position was accurately sensed by a coaxial 1 VDT embedded within the ball screw.

Requirements Comparison

Table 1 summarizes our understanding of the extent to which the inherited actuators would have to be either proved adequate or upgraded. Figure 2 shows what the MMVO actuator would look like if it met the functional requirements of Cassini.

Table 1

Initial Design Requirements for Actuator Development

Requirement (Disregarding Waivers)	Mariner Mars/Viking Orbiter	Cassini Multiple
Mission Duration	1.5 year mission	> 8 x
Longest Burn	0.75 hour	4.6 x
Length of Stroke	0.785 inch	1.43 x
Maximum Thrust Force		
Full Stroke Actuations	100	13 x
Small Motion Actuations	3,000 actuations of 0.02" under 130 lb load	27 x
Radiation Environment		

1 lifetime-related issues were obviously the most challenging to reconcile with the new Cassini mission. While there was a significant disparity between requirements, the actual life test results from the MMVO development were very encouraging. Also, there were no failures or anomalies reported in the earlier missions. As our investigation of the MMVO actuator progressed, however, other problems which had occurred in life testing surfaced. One way that these problems came to light was that we disassembled and inspected a MMVO actuator. For example, we found:

- The Kynar® shrink sleeve, which wraps the four wire leads of the service loop to the LVDI coil assembly, had become almost glass-hard
- There was a significant amount of brush wear debris present (we could not find a record of how much the actuator had been used)
- The LVDI ferrite probe displayed an alarming degree of wear
- High resistance and high starting voltage on one of the stored units
- The motor rotor had been epoxied to the ballscrew's nut because the small pin used for transmitting torque proved to loosen in operation,

Lesson 1: If you plan to use leftover hardware, test it, open it up as soon as possible and look inside.

Solutions to these problems are discussed below in the section on design upgrades.

We reasoned that it would be difficult to manage a development contract when requirements were still volatile, and there would be significant risk of design changes, so JPL committed to making the actuator assembly in-house.

Lesson 2: make commitments as early as possible.

We established that the basic EGA design was acceptable; parameters such as stroke length, lubricant type, load rating of mechanical components, etc. could all be worked through "business as usual". Enough time remained to do the inevitable redesign work that our pedigreed device would need.

What Spare Parts?

The first difficulty to slow progress was the availability of components for the inherited design. Although some spares had been stocked for the earlier missions, these either turned out to be substandard components or were undersized for the higher projected loads. Other parts simply had to be procured again. This was true for all major components including motors, LVDs, bearings, and ball screws.

Design Upgrade, Fabrication, and Test

Pressurized design

A feature of the actuator that we perceived to be important was its internal pressurized inert gas. Our actuators group had used this design feature to help ensure a favorable operating environment in previous hardware. Nitrogen gas at 5 psig and a trace amount of Helium for leak measurement was used. These gases were contained with static and dynamic O-ring seals, effectively excluding particulate contamination. Moreover, the seals mitigated concern of lubricant egress. The use of inert gas also promised to minimize motor brush wear for the life of the mission.

The MMVO actuators had been in storage for more than 17 years when we considered them for duty on Cassini.

We debated a long time about the need for internal pressure. On the one hand, our research indicated that even a fraction of a Torr (more than $\sim 1 \times 10^{-2}$ Torr) of inert gas was adequate to improve brush life, no matter what material combinations were selected. On the other hand, the twelve year mission presented us with the reality that internal pressure would certainly leak down to very low levels. This raised a concern that arcing due to the phenomenon of corona discharge could occur at an intermediate point in the mission's cruise phase. Further research indicated that, in a mix of gasses much like our actuator's, this phenomenon was most likely to occur at a pressure of about 0.1 Torr (Figure). To estimate end-of-life pressure conditions, we performed an analysis with three different assumptions: Worst-case leak, nominal leak rate as

measured from the MMVO actuators, and the best leak rate that we dared to hope. Ordinary (1-rings were assumed in the analysis; other, more positive seals would have required too much mass or volume.

The result of our analysis indicated that there was no realistic hope of maintaining pressures above the corona discharge level. This presented us with a choice: should we abandon the pressurized mechanism and invest all our hopes in achieving a full 12 year mission life with purely vacuum operation, or should we attempt a mixed approach of both pressurized and vacuum operation? Persuasive arguments on both sides of the issue did not lead to a clear choice. In the end, the flight heritage of the MMVO actuators gave us the justification to embrace the mixed approach. If it failed, we could fall back on purely vacuum operation.

Performance over temperature

As we progressed in modeling the new design, it became apparent that the MMVO actuators were not required to meet their performance specifications at temperature extremes. Cassini required more uniform performance over temperature, however, so this drove the following design considerations:

- Lubricant viscosity (use a high viscosity index lubricant, or a dry film)
- Bearing friction (minimize preload and preload change with temperature)
- Motor parameters such as resistance and torque constant

Search for a Motor

The original motors were designed and produced at a local Contractor. The original design was thought to be adequate, but there were two reasons why identical motors could not be manufactured: first, there were no extant prints in sufficient detail (perhaps there never were any!). Second, the Contractor was not interested in performing the follow-on work.

Even if the original Contractor agreed to produce more motors, WCI could not duplicate the materials and manufacturing processes of the original. Because any claim of heritage relies heavily on the ability to duplicate these factors, it would have been risky to proceed with the original vendor. Moreover, the requirement for minimum stray magnetic field was considered to be very firm, and the Contractor had no experience in designing for extremely low emitted fields. It was necessary to seek a new motor vendor and motor design.

One compelling feature of the MMVO EGA was its brush motor. Its simplicity compared to a brushless design made it very attractive and, because of the high radiation environment, commutation electronics for a brushless motor would present a significant

reliability problem. The Engine Gimbal Electronics (EGE) design was also fairly mature at this point, so changes to it were not welcome. Designing for adequate reliability in commutation electronics would have required allocations of power, volume, and effort that were in short supply. Finally, the available volume for the actuator constrained the outside diameter of the motor. With a smaller volume available for magnets on its rotating member, this means that a brushless motor cannot achieve the same flux density from its magnets as brush motor, and therefore would not be able to reach performance levels that Cassini required.

A Request for Information yielded several interested vendors. We specified that the vendors should present their experience in brush motor technology with special attention to vacuum applications,

At the same time, we began preparing a controlling specification for the procurement. Our search for literature to guide us in the specifics of brush motor design led to a document³ by the Fairchild Space Company. This guide gave us valuable insight into design features that need special attention. The following list quickly summarizes most of the significant design features that we controlled in our specification:

- Brush design parameters such as material, geometry, spring design, and contact pressure.
- Configuration design to accommodate brush debris without short circuiting,
- To survive the high temperatures in the vicinity of the thrusters, commutators should be designed for even higher local temperatures anti winding terminations should be welded to the commutator bars.
- The motor's rotor was locked to the shaft with two close-fitting keys so that it remained snug over many torque reversals.

We selected American Electronics Inc. (AEI) to produce our motors.

The Battle of the Brush

With the help of the reference from Fairchild, further literature search, discussions with brush vendors, peer reviews at JPL, and materials specialists' consultations, we elaborated on the above requirements in the specification. The objective was to reduce delays due to anticipated failure to a minimum. We learned that there was indeed a large content of "art" in the successful design and execution of a brush DC motor for vacuum applications. Most of this centered on brush-related design nuances.

Several details were specified to enhance the reliability of the motor. Cartridge-type brush holders were chosen over cantilever type. Corners of each brush holder were relieved to preclude binding in the presence of debris, and they were machined out of Vespel® to ensure stability over temperature. Average brush contact pressure and Spring parameters were listed. We chose to use undercut commutator segments, although a substantial amount of evidence suggested that no undercut was necessary.

The most important provision in our contract with the motor vendor was that an engineering unit must be built and tested as soon as possible. Our specification's test plan anticipated up to two failures in selecting an acceptable brush material; we required the vendor to identify at least two substitute brush materials and to present those at Critical Design Review for JPL's approval. Furthermore, these substitutes must be *immediately available* in the event that the previous attempt failed under any circumstances. Here is another lesson to apply, learned from "experience in potentiometer testing in the Topex/Posidon Solar Array Drive".

Lesson 3: To protect your schedule, test plans must include

- Rationale for why you perform a test (purpose)
- What the test is intended to accomplish (objectives)
- Contingency measures to take in case of failure (anticipated outcomes)

Table 2 is extracted from the motor specification test section. It delineates all of the environments and operating conditions required for the engineering motor life testing. The life test was performed in thermal/vac-turn conditions, with a constant torque load of 50% of stall, 28 Vdc excitation, and an inertial load of 144 g cm².

-Table 2

Sequence	Temp, °C ± 5 °C	Atmosphere	oscillating Motion ± 1 radian	Continuous Rotation 500/0 CW, 50% CCW
1	+ 20	1 atmosphere Nitrogen	942,500 radians	392,070 radians
2	+ 115	0.90 Torr ± 20%	141,375 radians	
3	+ 115	0.90 Torr ± 20%		43,375 radians
4	+ 115	< 1 E-5 Torr	141,375 radians	
5	+ 115	< 1 E-5 Torr		43,375 radians
6	- 25 - 75	0.90 Torr ± 20%	141,375 radians	
7	- 25 - 75	0.90 Torr ± 20%		43,375 radians
8-A	- 25	< 1 E-5 Torr	141,375 radians	
9	- 25 - 75	< 1 E-5 Torr		43,375 radians

A Cleaner Motor

Two other concerns drove the motor's design: Performance and stray magnetic fields. These are coupled to some extent. The required torque-speed curve is shown in

Figure . The original motor had acceptable performance, but exceeded the static magnetic field requirement of the Cassini mission by a large margin. We measured the unpowered, stray field of the overall MMVO FGA and found it to exceed 26 nT

The MMVO motor employs Alnico magnets to generate its stator field. We chose to use Samarium-Cobalt magnets for their higher energy product which, in turn, requires less volume to achieve the necessary flux density within the motor. We found that the MMVO motors were designed with the magnets in an orientation that exacerbated the offensive stray flux. The new motors used a different orientation whose magnetic circuit traps more of the flux within the steel stator ring (figure). Some of the flight actuators did not achieve the goal of 5 nT at 1 meter, but all reached very low levels from 11% to 25% of the MMVO values. The accomplishment is highlighted because it conflicts with a difficult mass constraint. More steel in the magnet ring would have improved our results even further.

Reconfigure for easier assembly and testing

The new FGA configuration is designed for ease of assembly and testing. It is built up from three modules, each with special tooling intended to shorten the calendar time required for many serial procedures in the MMVO actuator's single elaborate assembly. The larger ballscrew permitted the VDT's orientation to be reversed, thus opening up several opportunities for reliability-enhancing improvements. The tooling dedicated to each subassembly made it easy to catch assembly and fit-up errors early, without puzzling over what part of a fully assembled actuator is responsible for unexpected problems.

Lesson 4: Invest early in planning the assembly and test sequence. Attempt to isolate mechanism subassemblies at a reasonably simple level, where their fits and performance can be checked against expectations. This approach is often perceived as an unnecessary extravagance and omitted from small lot production runs. Not only will problems be identified at an early stage, but the consequences of not meeting a published specification for the full assembly can be avoided.

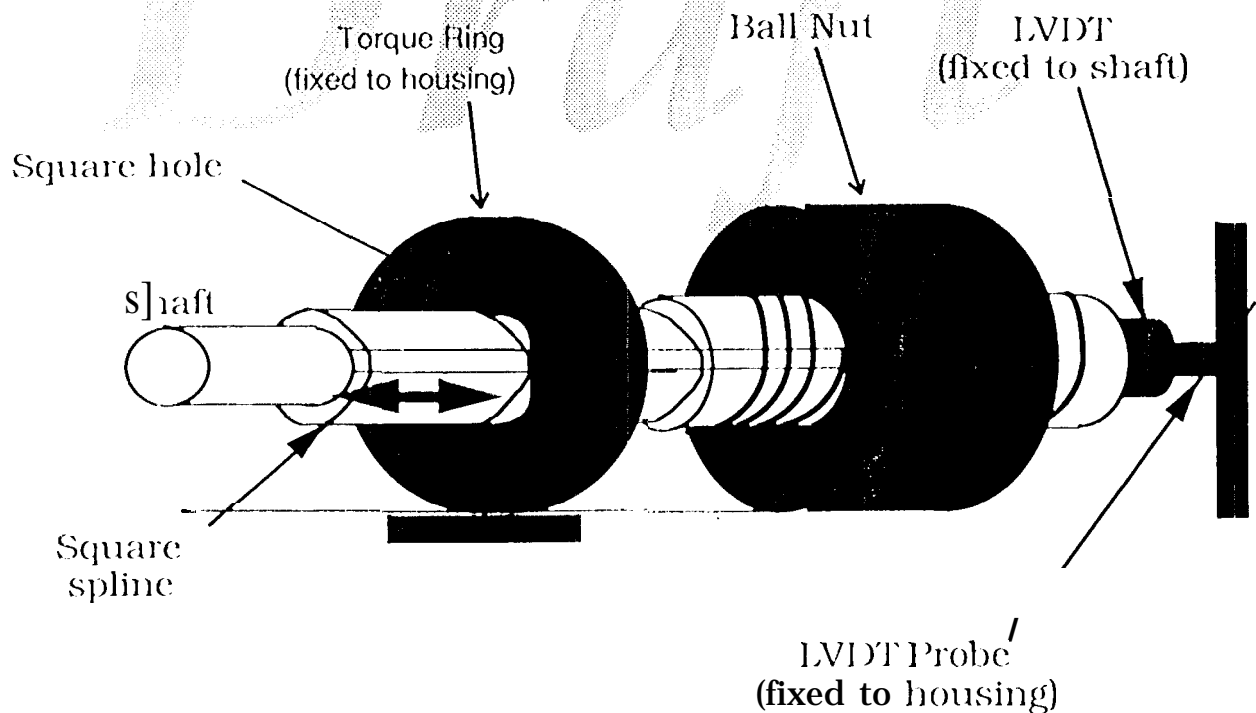
Bearings and Ballscrew

The original ball bearings were no longer available. The original manufacturer was not interested in making new bearings to an old part number for our small quantity. We prepared a new specification for competitive quote, with particular attention paid to >>>>>>>>>>>>.

The MPB bearing company responded favorably to our request. We elected to buy a commercial "extremely light" standard section made out of 440C stainless steel. This resulted in a healthy margin of load capacity as the bearing's thrust rating was more than twice that of MMVO's original bearings. Next, we substituted a larger **20 mm**

outside diameter ballscrew to replace the older 16 mm diameter component. As with the larger ball bearings, this change increased mass.

Although not necessarily required for load capacity, the extra mass paid important dividends. These choices promised the shortest possible lead times and least likelihood of errors in manufacturing. Several vendors could more easily quote to industry-standard size bearings and ballscrews. Moreover, our older ballscrews displayed a large variation in friction and backlash. Ballscrew manufacturers agreed that this change promised to yield a more uniform component. The net effect of these decisions was to minimize schedule risk.



Use a Real Lubricant

One important lesson the JPL has learned from its experience with the Voyager Spacecraft is that the lubricating fluid used in some of its mechanisms was not a real lubricant at all. Versilube (2-300 silicone grease and f-50 fluid) were employed then. When they first became commercially available, silicone fluids held tremendous attraction because of their low vapor pressure and high viscosity index-- stable viscosity with temperature variation. Problems with the scan platform mechanisms led to research that showed silicone fluids are non-Newtonian. Worse yet, the hygroscopic fluid turned into a gritty paste of microscopic crystals under high shear conditions in the presence of water.

In keeping with the conservative project guidelines, we selected Bray 600 grease/8157 oil to replace the old lubricant. Special provisions were designed-in to ensure a

lubricant reservoir for the ballscrew slider and ballnut. To minimize friction, the ball bearings were loaded with relatively little grease, but they are sealed on both sides with contacting lip seals.

Use a Flexure, Reverse the LVDI

One of the most disturbing findings when we disassembled the MMVO actuators was the degree to which the LVDI probe had worn. It turned out that this had been noticed before, but not documented. The reason was that each end of the LVDI was held in a separate subassembly of the actuator, and there was a substantial tolerance build-up between the two parts. We remedied this by mounting the LVDI ferrite probe on a 1.52 mm (0.06 inch) diameter flexure rod. This forced us to use careful, handling methods while assembling the actuator to avoid bending the flexure, but the approach allowed us to analytically bound the stresses and forces acting on the probe hardware.

Lesson 5: Risk is mitigated whenever an analytically determinate design is employed.

Soft Stops

One consequence of a peer review is that it will often generate new requirements. We realized that the MMVO actuator did not have a design feature specifically for absorbing the mechanism's energy at its end of travel. With the help of our materials engineers, we designed custom-molded urethane stops to cushion the ballscrew at each end of travel. The wide temperature range made this a particularly challenging materials problem.

Slippery Restraint

MMVO actuators employed a simple, square spline to resist the ballscrew's tendency to rotate. We considered improving the design with a sophisticated involute spline, but eventually settled on a flat, broad rectangular section with brass slipper plates. The final design results in less backlash while permitting the same reasonable tolerances.

Magic Vespel

The MMVO actuators' u-joints employ bushings made of Dupont Vespel. While redesigning these for the higher anticipated loads, we investigated alternatives for the material too. In a Space Mechanisms Videoconference⁵ we learned that Vespel has the valuable tribological property of *reducing* its coefficient of friction in vacuum, in contradistinction to most other materials that we have knowledge of.

New Rod End

Lining and lubricant changed from Teflon to MoS₂.

Maintenance Actuators

No procedure had been established to regularly "exercise" the MMVO actuators. After investigating brush motors, however, we determined to proceed with caution. "Cold welding" or vacuum welding of asperities between the brushes and commutator posed a significant risk in a very long 12 year mission. Even though the brush/commutator material combination was selected for maximum reliability, we still feared that a non-conductive film may build up under the brush. This phenomenon is illustrated by our measurements of MMVO actuator characteristics. When we first pulled the machines out of mothballs, our first impulse was to "fire them up" and see how they would run. Restraining ourselves, we instrumented the power supply first, and measured the resistance at the motor's terminals. We found resistance as high as 10 K Ω and, starting voltage as high as TBD. After a few strokes, the starting voltage settled down to TBD. Later on, we subjected the parts to analysis and found commutator corrosion products and silicone F-50 fluid on the commutator's surface. The supply voltage was nominally 28 volts.

To avoid any concern over this problem, we initiated a flight rule requirement that the flight actuators would be operated every 6 months, whether in ground storage or in space.

Lesson 6: Unless time and money resources prohibit, don't plunge ahead and test hardware without a carefully thought-out idea of what, why, where, and how you will do your test.

Final Embodiment

Force-Speed Curve

Requirements comparison

Requirement	Mariner Mars/Viking Orbiter E GA	Cassini E GA	Design Change Code
Mission Duration	2.8 years	12 years	A, B, K
Longest Engine Burn	45 minutes	3.5 hours	F, K
Total Operating Time	2 hours	142 hours (somewhat ambiguous)	A, C, K
Range of Motion	0.785 \pm 0.030 inch	1.120 \pm 0.040 inch	C, D, E, H, I
Number of Full Stroke Actuators	100	1,300	C, D, E, H, I

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Requirement	Mariner Mars/Viking Orbiter EGA	Cassini EGA	Design Change Code
Number of Small Actuators (up to 1/20 of total stroke)	3,000	80,000	A, C, D, E, H, L
External Magnetic Fields: • Static • Dynamic	N/A 5 nT @ 1 meter	2.5 nT @ 1 meter 5.0 nT @ 1 meter	F
End of Travel Stop Integrity	N/A	No damage at full rate crash with 105 kg REA equivalent inertial load	D, G, L
Severe Launch Loads	?	Thrust = 827 N (188 lbf) Lateral = 71 G on 2 axes	C, G, I, J, L

Future Improvements

More lubricant

¹ Hudolph, Dale. Design and Development of the Cassini Main Engine Assembly Gimbal Mechanism, 30th Aerospace Mechanisms Symposium, May 1996, Denver Flight Systems, Lockheed Martin, Denver, CO
² Paine, T. O. and Perkins, G. S. U.S. Patent No. 3,660,704, May 2, 1972
³ Morin, John P., General Guidelines for Brush Motor Spaceflight Applications, April 24, 1992, Fairchild Space Co., Germantown, MD

Don't forget the CDR Volumes

Don't forget the motor brush memo and the motor performance memo.

⁴ Iskenderian, Ted. Lessons Learned From Selecting and Testing Spaceflight Potentiometers, 28th Aerospace Mechanisms Symposium, May 1994, California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA

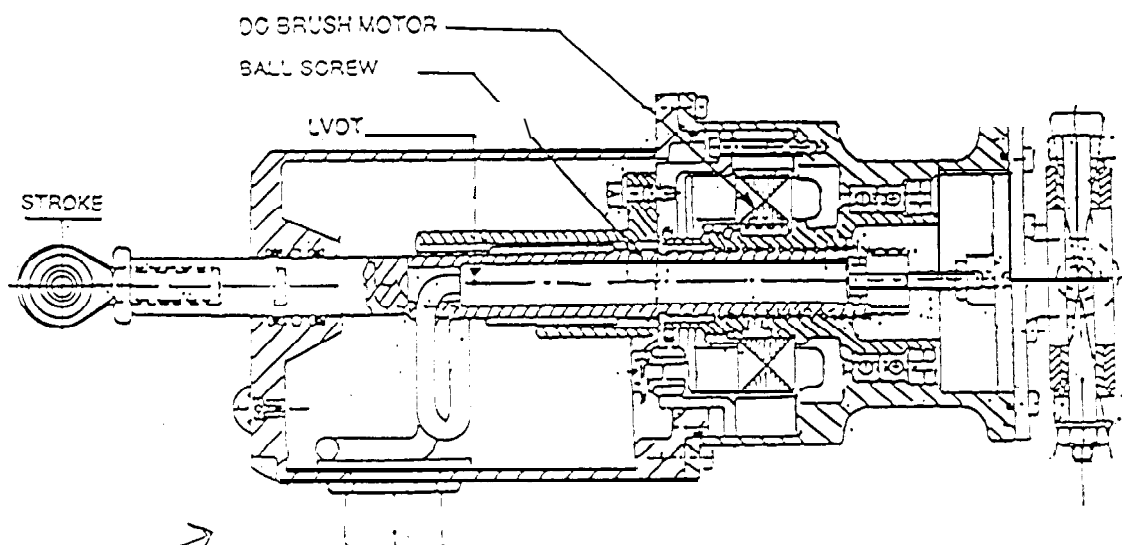
⁵ Siebert, Mark. Report on polyimide roller friction in vacuum vs. air, Space Mechanisms Videoconference, hosted by Robert Fusaro at NASA Langley Research Center, December 13, 1993

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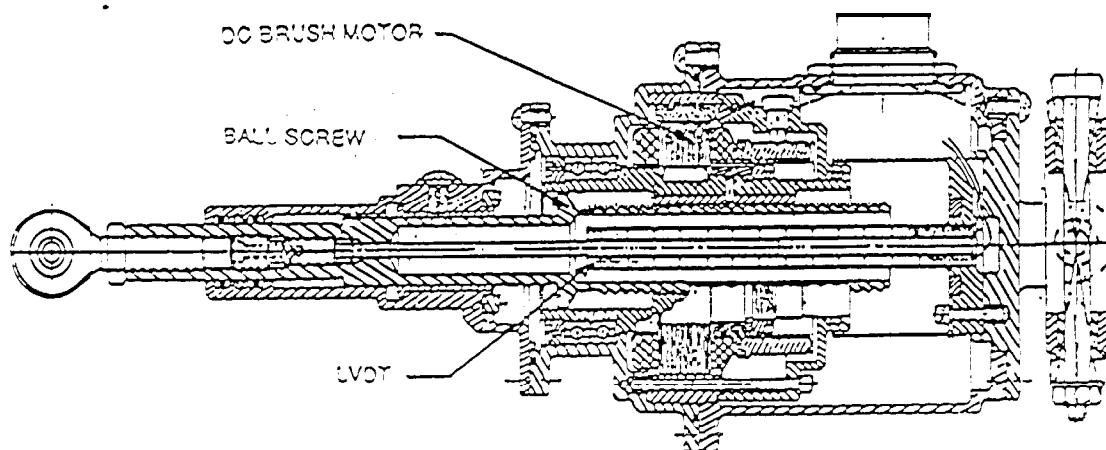


Engine Gimbal Actuator

Design Evolution



VIKING design concept
shown with Cassini
length & stroke ,
WHICH IS EMBODIED USING
THE CONCEPT DESIGN, BASED ON THE
US PATENT NO. 3,660,704



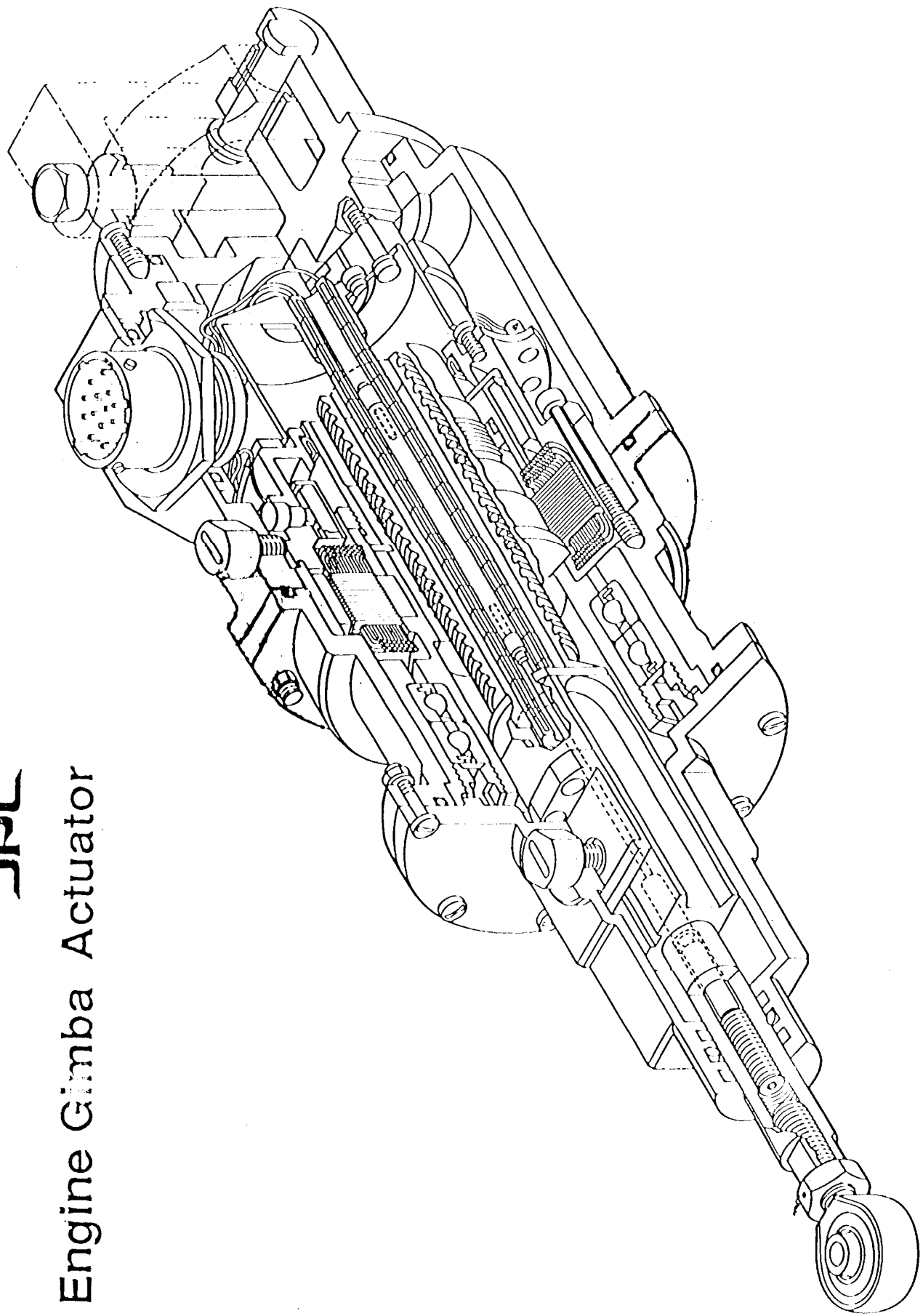
NEW CONCEPT DESIGN

CASSINI implementation

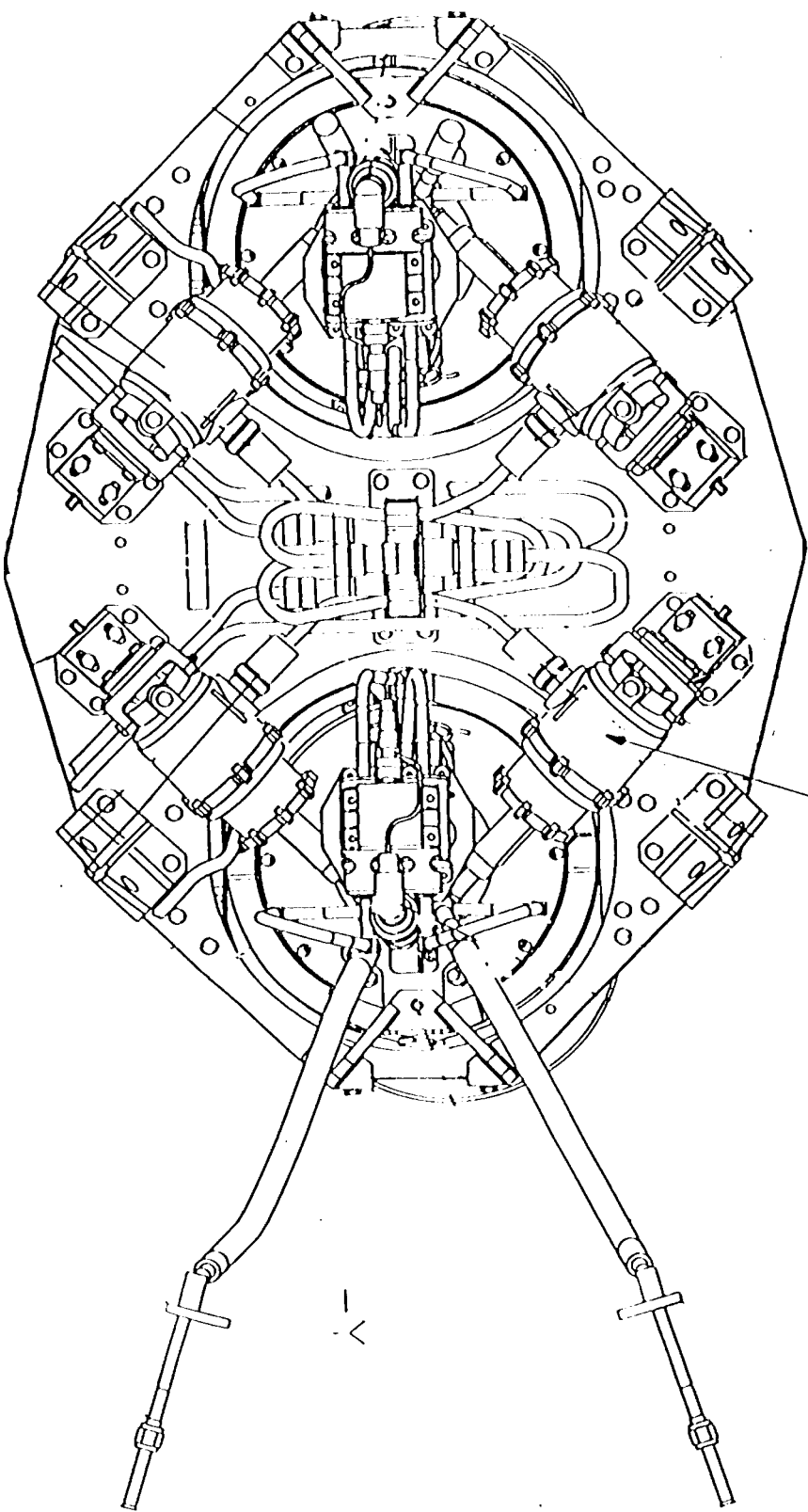
- Stationary wiring
- Soft travel stops
- Minimized external magnetic fields

FIGURE NO. 2

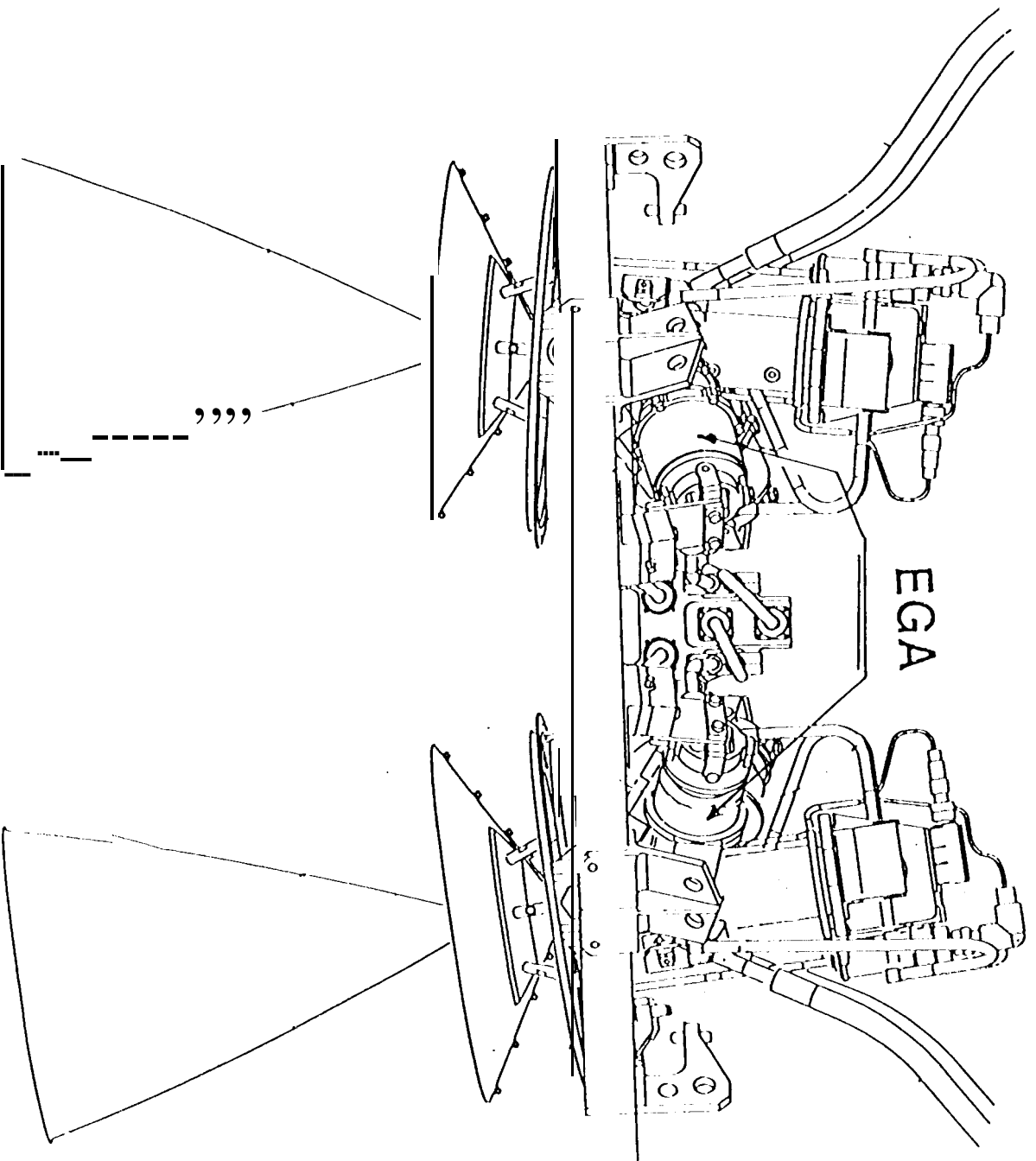
JPL
Engine Gimba Actuator



EGA



MEA LAYOUT

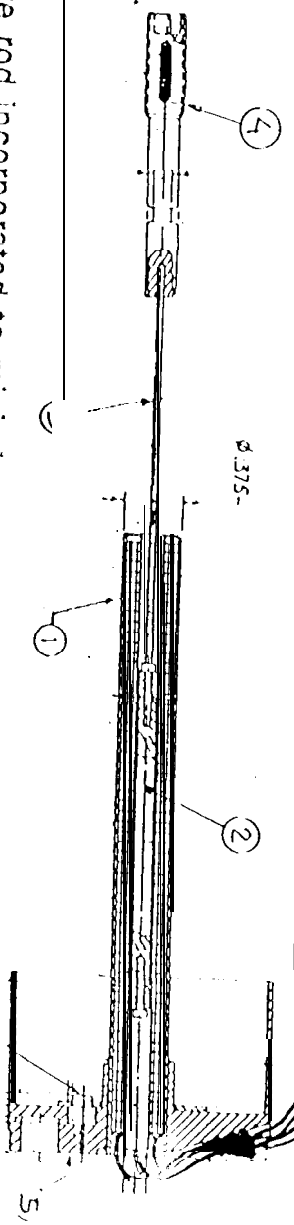


MEA LAYOUT

JPL

Linear Variable Differential Transducer

D LVDT re-configured, re-oriented to eliminate flexing service loop



E Flexure rod incorporated to minimize normal force at sensor slug/coil interface. Eliminates wear out mode and wear debris